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This AASERT grant supported two students, Michael Meyers for three years and Scot C. Randell Rafkin, for the last six months. Most of the research has been conducted by Mike Meyers developing the new microphysical scheme which was implemented into RAMS. This new scheme allows prediction on both the concentration and mixing ratio of the distribution function for each hydrometeor category making the determination of each hydrometeor size spectra less arbitrary. With More detailed physics the model should have the potential to allow for the evolution of the hydrometeor spectra. The new microphysics also allows prediction of an additional hydrometeor species, hail. Mr Rafkin (formerly Randell) research has been directed towards the development of a convective parameterization valid for numerical models with grid spacings ranging from the mesoscale to GCM-like scales.

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For Period 1 June 1993 – 31 May 1995

REFINEMENTS IN CLOUD MICROPHYSICS AND 4DDA IN SUPPORT OF NUMERICAL CLOUD PREDICTION

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This AASERT grant supported two students, Michael Meyers for three years and Scot C. Randell Rafkin, for the last six months. Their grades were satisfactory for the duration of this grant. The DOD basic research agreement (parent award) number is AFOSR-91-0269.

1 Final Technical Progress

1.1 Research Conducted by Michael Meyers

Most of the research has been conducted by Mike Meyers developing the new microphysical scheme which was implemented into RAMS. This new scheme allows prediction on both the concentration and mixing ratio of the distribution function for each hydrometeor category making the determination of each hydrometeor size spectra less arbitrary. With more detailed physics the model should have the potential to allow for the evolution of the hydrometeor spectra. The new microphysics also allows prediction of an additional hydrometeor species, hail. Some highlights of the model include:

- the use of a generalized gamma size-spectrum where the ν parameter can be prescribed by the user as opposed to a fixed Marshall Palmer spectrum
- the introduction of ice-liquid mixed phase graupel and hail categories categories with non-thermal equilibrium for the rain, graupel and hail classes
- new heterogeneous and homogeneous ice nucleation parameterizations
- approximate solutions to the stochastic collection equation rather than the continuous accretion model approach
- breakup of rain droplets is formulated into the collection efficiency
- analytical flux equations predict mixing ratio and number concentration conversion from pristine ice crystals to snow due to deposition (no riming)
- predictive equations for ice nuclei (IN)
- crystal habit is diagnosed dependent on temperature and saturation
- evaporation and melting of each species assumes that the smallest particles completely disappear first
- more complex shedding formulations which take into account the amount of water mass on the coalesced hydrometeor.

After testing the new scheme, two case studies were examined, a wintertime orographic precipitation event over the Front Range of Colorado from the Winter Icing and Storms Project (WISP91), and a summertime convective case over the High Plains of Montana from the Cooperative Convective Precipitation Experiment (CCOPE81). These cases allowed comparisons between the two-moment predictive scheme and the one-moment predictive scheme and highlighted the advantages of independently predicting on two moments of the hydrometeor spectra. Detailed analysis was also done on these two cases with special attention given to radar reflectivity, aircraft, and ground-based measurements.

Other research conducted during this period includes:

1. quantitative precipitation forecasts of wintertime orographic cloud from the Sierra Nevada range of California

2. implementation of natural and artificial primary ice nucleation parameterizations for use in cloud models

3. formulation of parameterizations for homogeneous freezing of cloud droplets and haze particles which are relevant to ice initiation of cirrus clouds.

1.2 Research Conducted by Scot C. R. Rafkin

Mr. Rafkin (formerly Randell) has been funded under the current AASERT proposal for approximately the last six months. His research has been directed towards the development of a convective parameterization valid for numerical models with grid spacings ranging from the mesoscale to GCM-like scales. A summary of his research is presented below.

1.2.1 Objective

Currently, a cumulus parameterization which is valid at the mesoscale does not exist. A few schemes have been developed which can be applied at scales larger than about 50-100km (*e.g.* Fritsch and Chappel (1980); Kreitzberg and Perkey (1976)). However, more often than not, parameterizations which have been developed for large-scale models, such as Arakawa and Schubert (1974) and Kuo (1965), are applied at smaller mesoscales despite the approximations and assumptions which become increasingly questionable as the grid spacing decreases. Furthermore, modellers are faced with having to choose, somewhat arbitrarily, different parameterizations for different scales. The goal of this research is aimed at developing a cumulus parameterization which is valid over a wide range of scales, with particular focus on at the mesoscale. The new parameterization will eliminate the need for different parameterizations at different scales, and free the modeller from having to decide when to change from one parameterization to another.

1.2.2 Philosophical Foundation

Before the parameterization can be designed, we must consider what it means to parameterize cumulus convection at various scales. In the case of large-scale parameterization, the statistical effects of an ensemble of convection is considered. We define an ensemble of clouds to be the set of all possible clouds which could exist in a given environment. In the Arakawa-Schubert parameterization for example, all possible clouds which could exist (the ensemble), do exist; that is, they contribute to the cumulus forcing of the large-scale environment. As long as the area we are considering is large enough to contain the ensemble, this approach is valid.

Clearly, as a model grid box shrinks, a point will be reached where it is not possible to physically fit the ensemble within the given area. If we wish to know the effects of cumlus convection on the model-scale variables, however, we still need to know which types of clouds are in the box. We define the active population to be the subset of the ensemble which is actually found within a given area. We can make an educated guess at the active population by considering which type of clouds are more likely to be found within a given

area. Of course, the actual cloud population within the area will generally differ from our guess, but on the average we will be correct.

Determining a probability density function for an ensemble of clouds will be one component of the parameterization. Once we know the probability for the existence of each type of cloud in a given environment, we can select the active population for a given area. Large-scale models with large grid spacings will contain the entire ensemble since there will be room for even the most unlikely members. As the grid spacing decreases, we will use the PDF to select the active population.

In addition to the selection of an active population, we must also consider that the effects of the convection, in particular the subsident circulations, may extend beyond the grid box boundaries. In large-scale parameterizations the effects of the cumulus ensemble are assumed to remain wholly within a grid box—a horizontally local event. Therefore, as we transition from large to small grid spacings, we also transition from a horizontally local parameterization to a horizontally non-local parameterization. We conclude that the area over which the parameterization is applied should not be a function of the grid resolution. Rather, it should be applied over the convective influence area (CIA), or the area over which the convective circulations extend. Determining the CIA will be another component of the parameterization.

1.2.3 Parameterization Design

Prognostic Cumulus Kinetic Energy

Following the work of Lord and Arakawa (1980), and Randall and Pan (1993), we introduce the prognostic cumulus kinetic energy (CKE) equation:

$$\frac{\partial K(\lambda)}{\partial t} = (A(\lambda) - D(\lambda))M_B(\lambda), \tag{1}$$

where K and M_B are the vertically-integrated kinetic energy and the cloud-base mass flux per unit area, respectively, associated with the sub-ensemble of clouds in the interval $(\lambda, \lambda + d\lambda)$. The cloud work function, A, and D are the generation and dissipation, respectively, of K per unit cloud-base mass flux. As proposed by Xu (1991) and Arakawa and Xu (1990) we relate K and M_B through the constant α as follows:

$$K = \alpha M_B^2. \tag{2}$$

Combining Eqs. (1) and (2), and assuming that α is independent of time yields a linear differential equation for the time rate of change of the sub-ensemble cloud-base mass flux:

$$\frac{\partial M_B}{\partial t} = \frac{A}{2\alpha} - \frac{M_B}{2\tau_d}, \tag{3}$$

where the dissipation term has been modeled as $D = K/\tau_d$. Given the parameters α and τ_d for each sub-ensemble, we can predict the evolution of their associated cloud-base mass flux. Currently we are using fixed values for both parameters, but future research is intended to provide more realistic parameterizations of these quantities.

The above method of determining the cloud-base mass flux is in contrast to the classical technique typically employed in the Arakawa-Schubert parameterization. We note that the prognostic equation given by Eq. (3) is computationally much more efficient. In addition, it

does not require partitioning or separating the large-scale forcing from the cumulus forcing. The implications of the closure are discussed in more detail in Randall and Pan (1993).

Determining the PDF and Active Population

The cloud work function for each sub-ensemble is computed using a plume model. Following Simpson and Wiggert (1969) we can calculate the in-cloud vertical velocity profile and kinetic energy. Let $K(\lambda)$ be the vertically integrated kinetic energy of the plume-cloud of type λ. Then,

$$K(\lambda)\Delta \equiv n(\lambda)\sigma(\lambda)K, \tag{4}$$

where Δ is the area in which the sub-ensemble is present, n is the number of λ clouds and σ is the vertically averaged cross-sectional area of the a type λ cloud. The quantity $n\sigma$ is the total area occupied by each sub-ensemble, and is used to determine the probability distribution function (PDF) and active population. By normalizing this quantity, we obtain the PDF.

There are two methods to determine the active population. The first method involves choosing the most probable cloud types from the PDF, and allowing only as many sub-ensembles that will fit within the model grid box. The total area of the active population is simply the sum of $n\sigma$ over the chosen cloud types. This procedure will only provide the effects of the most probable clouds and never include any effects from more unlikely cloud types. After choosing the active population, we set the cloud-base mass flux for each sub-ensemble not selected equal to zero. Of course, this allows the cloud work function for the unselected sub-ensembles to increase with time since there is no stabilizing convective effects allowed. Eventually, the cloud work will increase enough that the clouds "move up" the probability scale and are selected.

In the second method, the quantity $n\sigma$ is normalized by the grid box area. This new distribution function then represents the fraction of each sub-ensemble that could exist in a grid box. The cloud-base mass fluxes are then multiplied by this quantity when determining the cloud forcing. In this method, all clouds, even the unlikely ones, have an influence. Following the determination of the active population, the cloud-base mass fluxes are normalized by the PDF.

It is not clear yet which method should be chosen. Once preliminary testing is completed, we will undertake simulation using both methods to try and determine the more appropriate method.

Computing Grid-scale Tendencies Due to Clouds

Given the active population within a grid box, we can determine the average tendencies of the environment variables, ξ_e, due to each sub-ensemble in the active population through the divergence of the cumulus fluxes which are modeled as:

$$\rho\overline{w'\xi_e'} = M(\xi_c - \xi_e), \tag{5}$$

where M is the total cloud mass flux due to the active population, and the subscripts c and e refer the cloud and environment properties, respectively. However, the average tendency is *not* valid over the model grid. It is valid over the CIA for the particular sub-ensemble which may in general cover many model grid boxes. We therefore need to determine the CIA associated with each particular sub-ensemble within the active population.

We assume that the subsident circulations due to a cloud are bounded by the wavefront of an internally propagating gravity wave. This assumption has been verified by observation

(Mapes, 1993) and also by numerical experiments (Nicholls *et. al*, 1991). The speed of the wavefront is obtained through linear gravity wave theory (*e.g.* Holton (1979)), and includes Doppler shifting due to the mean environmental flow.

Given the area bounded by the gravity wave, the individual grid box tendencies are computed using the grid volume averaging operator defined by:

$$G(x) = \sigma_c x_c + (1 - \sigma_c)x_e, \tag{6}$$

where σ_c is the fractional area within a grid box occupied by clouds. In our case, it will be the total area occupied by the active population divided by the grid box area. We require that the sum of the model grid tendencies within the CIA be equivalent to the average tendencies computed from the Arakawa-Schubert parameterization. Therefore, if we let a_{ij} be the area fraction of the total CIA of a grid box (i, j) at least partially located within the CIA, any average quantity must conform to the following:

$$\overline{\xi} = \sum_{CIA} a_{ij} G(\xi_{ij}). \tag{7}$$

The model grid tendencies are computed such that the average of the tendencies in the model grid box which contains the sub-ensemble, and the tendencies in the neighboring grid boxes which are within the CIA are exactly equal to average tendency computed over the CIA. Solving the system of equations above provides the grid box tendencies.

Cloud Propagation

Each sub-ensemble may advect from one grid box to another. We use the cloud-base mass flux obtained from the prognostic mass flux equation as a tracer for each sub-ensemble. For simplicity, we choose the advective velocity to be the average horizontal wind over the depth of the cloud. Eventually, this may be modified to include other terms, for example, to model the effect of gust fronts on storm propagation, or storm vorticity or helicity to model, right and left moving cells.

Summary of Parameterization Methodology

We now summarize the methodology of the parameterization:

- Using a cumulus ensemble model, determine the sub-ensemble properties and cloud work function.
- Integrate the prognostic mass flux equation.
- Using the Simpson-Wiggert method, calculate the vertically-integrated kinetic energy of each sub-ensemble.
- Solve for the quantity $n\sigma$–the total sub-ensemble area.
- Determine the PDF and select an active cloud population.
- Determine the CIA for each sub-ensemble.
- Determine the tendencies valid over the CIA by taking the divergence of the cloud fluxes.
- Determine the model grid tendencies such that they average to the CIA tendency using the grid volume averaging operator.

- Advect the cloud sub-ensembles using the cloud-base mass flux as a tracer.
- Repeat the procedure on the next time step.

1.2.4 Conclusion

A cumulus parameterization suitable for a wide array of model grid scales has been described. The parameterization is fundamentally different than presently available parameterizations because of its grid size independence, its horizontally non-local nature, and use of a PDF to determine the active population from the sub-ensemble. The scheme is numerically efficient so that regional scale and operational numerical models can potentially benefit greatly from its implementation. Forecasts obtained from this parameterization will represent the most probable cloud forcing based on our determination of the PDF.

We have just begun to code the parameterization and as of yet do not have any results. At this point, the code is being tested for accuracy and efficiency. We do expect a β version of the parameterization to be implemented shortly.

Also, we have been conducting three-dimensional cloud ensemble simulations to try and better parameterize some of the unknown parameters such as α and τ_d. The data from these simulations has not yet been analyzed.

Mr. Rafkin is expected to complete the preliminary implementation and research associated with this parameterization within the next year. Progress made in the future will be described in his dissertation as well as other intermediate reports to the AFOSR/AASERT contract under which he is currently funded.

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